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A SYNCHRONOUS CONVERTER POWERED PLASMA GENERATOR SYSTEM

By

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A portion of a Master of Science
Thesis in Engineering.

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ABSTRACT

A plasma generation system powered by a synchronous converter power supply was designed and constructed. Two separate plasma generator models, designated as the tip-tube unit and the tube-tube unit, were developed and operated satisfactorily. The necessary supporting equipment, comprising the electrical power, cooling water, plasma gas and magnet subsystems, was designed and fabricated for use up to a power level of one megawatt.

The power utilized by the two plasma generators during the performance investigations was in the 75 to 125 KW range. The enthalpy and temperature of the resulting plasma stream was estimated to be 2500 to 4500 BTU/lb and 6000 to 9000°R, respectively. Analysis of these results and consideration of the capabilities of the system indicates that it is possible to obtain ranges of plasma stream enthalpy and temperature of 1000 to 8500 BTU/lb and 4000 to 11,500° R, respectively. The most satisfactory operation was obtained with the tip-tube unit. However, with modification of the anode of the tube-tube unit equally successful operation is anticipated.

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I. INTRODUCTION

The increased interest in achieving high temperature and high heat flux environments has led to extensive development in the field of plasma generators--by common definition, electric arc devices for the sustained heating of gases to high temperatures. Such devices have many possible uses, including: chemical synthesis; the working of refractory materials; high temperature and high heat flux research; space propulsion; and simulation of re-entry heating.

Several recent state of the art articles and reports[1,2,3*] review rather completely the development of the plasma generator and its current applications. These sources point up many interesting items, including a commercial proprietary interest aspect, which frequently causes the technical information released to be quite general in nature. Another item of particular significance is that while many plasma generators have been built, there are actually only several basic configurations. Also pointed out is the fact that because of incomplete understanding of the electric arc phenomena there is little in the way of applicable theory that can be used for a particular design. Because of this, it has been found necessary to depend on experience with specific plasma generator configurations in the design of new units, incorporating the necessary modifications and improvements for the applications desired.

This last point was of primary concern in the present study. For, although the main objective was to develop a plasma generator for producing high heat flux conditions, it was to be powered using direct current from a synchronous converter power supply. This power supply essentially consists of transformers, the synchronous converter, and a

[*] Superscript numbers indicate the References.

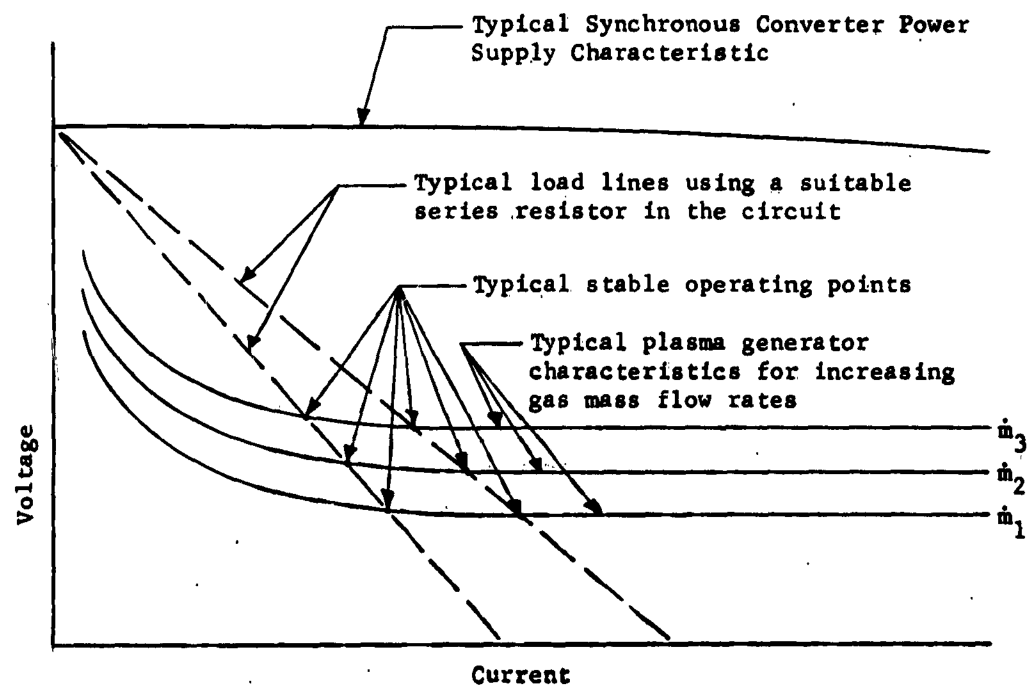

FIGURE 1. TYPICAL PLASMA GENERATOR AND POWER SUPPLY CHARACTERISTICS

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set of automatic station control equipment. The system, controlled by the automatic station control equipment, utilizes the synchronous converter to transform the multiphase alternating current power from the transformers to a direct current output. The available device is typical, being capable of providing up to 1500 amperes in the 500 - 700 volt range with a nondrooping characteristic as illustrated in Figure 1. This introduces a stability problem, in that plasma generator characteristics are likewise of a non-drooping nature over the current range of greatest interest (i.e., 200 - 2000 a.). Also, the voltages used for plasma generator operation are comparatively low (i.e., 20 - 150 V). In view of this fact, the adaptation of the synchronous converter power supply to operate a typical plasma generator can be achieved by the addition of a suitable ballast resistor in the circuit. This provides a stable operating arrangement, in that a decreasing

voltage with increasing current characteristic is supplied to the plasma generator. This provides the sharp power supply-plasma generator characteristic intersection necessary for stable operation in the range of lower voltages encountered (see Figure 1). A consequence of using a ballast resistor with the synchronous converter, however, is that a substantial amount of power will be lost in the resistor. This can only be minimized by selecting a plasma generator model which operates with a large voltage drop.

In adapting the synchronous converter power supply for powering a plasma generation system and considering the possible applications for such a system along with the absence of a vacuum facility, the following general guiding criteria were adopted for the design of the plasma generator:

1. The efficiency of the plasma generator should be as high as possible (i.e., $\eta \geq 50\%$).
2. The gas flow should be heated to as high an enthalpy level as possible (i.e., 2000 - 10,000 BTU/lb) to assure high temperatures and heat flux rates.
3. The gas flow should be uniformly heated and as free as possible from local unevenness, vorticity and turbulence.
4. The resulting plasma stream should be as free as possible of contaminants.
5. The plasma generator should be capable of steady operation for periods of at least ten minutes.
6. The plasma generator should be capable of utilizing as much of the direct current power from the power supply as possible (i.e., the maximum power for short periods of operation is about one megawatt).

7. The plasma generator should exhaust into the atmosphere.
8. The nominal resulting plasma stream diameter desired is one inch.

Study and analysis of the pertinent literature were then carried out to select a design which would best satisfy the above requirements.

II. PLASMA GENERATOR SYSTEMS

A. Current Plasma Generator Designs

Review of the available literature, including both state of the art papers and specific investigation reports, indicates that most of the devices constructed have several general features in common. These features, as outlined by John and Bade,[1] include:

1. Approximate rotational symmetry about a central axis.
2. Coaxial electrodes separated by an annular gap, across which the current flows.
3. Some technique for producing and controlling arc motion on the electrode surfaces, especially the anode.

The first two of the above assure that some part of the gas flowing through the unit will pass through the arc region where heating occurs. The third feature is necessary because the natural arc motion often causes instability and extinction or, for the higher power levels, electrode damage. Forced arc motion also provides increased contact with the gas flow, besides the longer electrode life and the accompanying lower levels of plasma contamination. The non-uniformity of the resulting plasma stream is the main undesirable aspect of inducing arc motion.

Further evaluation of the types of plasma generators leads to the consideration of only direct current devices. This is because of the almost

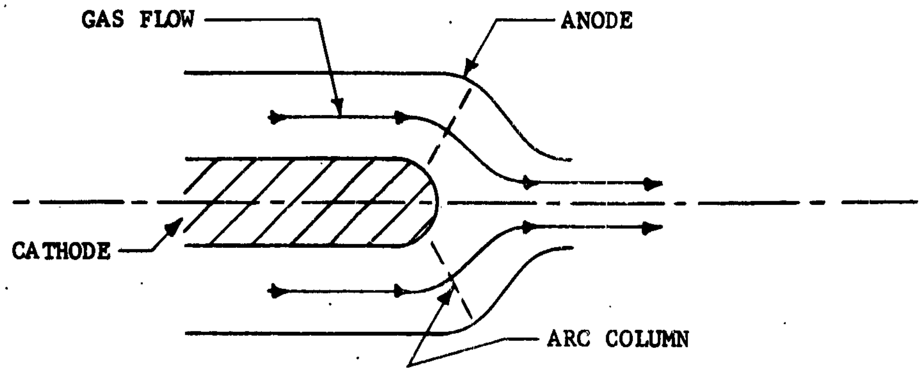
exclusive use of direct current power for plasma generation. A very limited number of alternating current and radio frequency powered devices have been built and tried, but for various reasons they have not been too popular.[4,5] Most direct current powered plasma generators can be classified on the basis of the electrode configuration. Those units which can be distinguished by the electrode configuration fall into one of the following three categories:[1]

1. A cylindrical configuration
2. A toroidal configuration
3. A constricted configuration

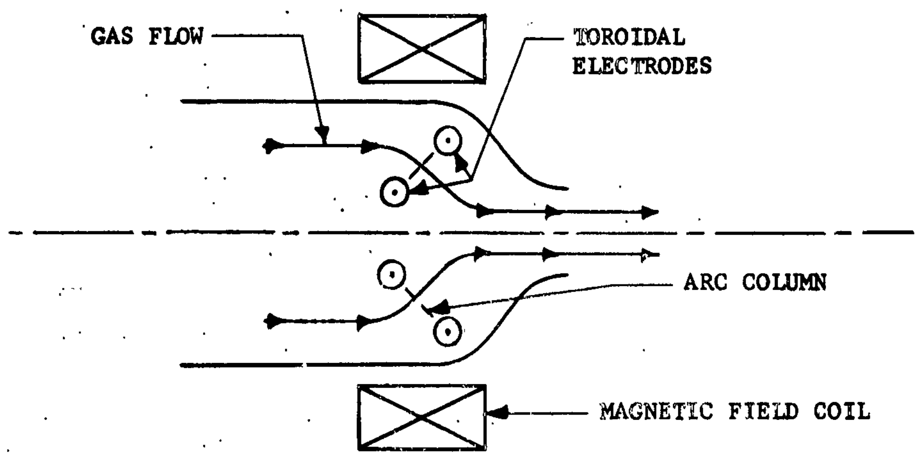
Numerous versions of each of these have been constructed, but differ in geometrical details, cooling, electrode materials, gas injection and magnet applications. The basic configurations are illustrated in Figure 2.

The simplest of the three categories is the cylindrical configuration (Figure 2a). It has a refractory central cathode surrounded by a water cooled metal anode.[6,7,8] The anode often leads into a converging nozzle through which the plasma stream exhausts. Many of the models of this configuration use an aerodynamic means (i.e., the tangential injection of gas into the arc chamber) to rotate and thus stabilize the arc on the anode. Other models use a magnetic field to produce the desired arc rotation.

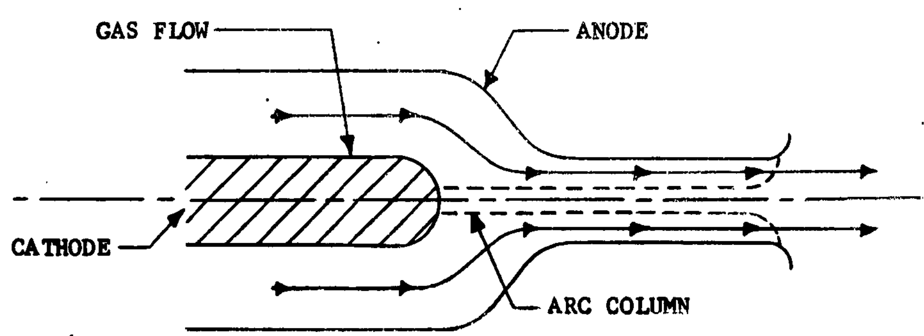
In the toroidal configuration (Figure 2b) the electrodes are essentially two water cooled metal rings having the same centerline, but different diameters, and usually some axial spacing.[7-11] The current path is across the annular gap separating the rings, and is forced to rotate by externally applied magnetic fields (a vortex gas flow is not sufficient or desired). This configuration is primarily intended for the heating of



(a) A CYLINDRICAL CONFIGURATION



(b) A TOROIDAL CONFIGURATION



(c) A CONSTRICTED CONFIGURATION

FIGURE 2. PLASMA GENERATOR CONFIGURATIONS

gas flowing axially, where such a flow is a very desirable property in the resulting plasma stream. Units of this type, however, can quickly suffer failure because of magnetic field change or collapse, cooling water flow variations, electrode surface imperfections and slight misalignment between the rings.

The last category is that of the constricted configuration (Figure 2c), where one electrode is upstream of a duct making up the other electrode.[6,9,12-22] Both refractory and water cooled metal electrodes are used in either position, with the upstream electrode being in a variety of shapes. These units most often operate with the duct electrode as the anode and the upstream electrode as the cathode, but examples exist where the polarity is reversed. The current and voltage available, amount and type of gas flow, magnetic field, and geometry details determine the arc attachment point in the duct electrode. This configuration with the confinement of the arc column by the duct has been shown to allow stable "long" arcs aith their increased column voltage drop, current density, and arc temperature; the other configurations primarily operate only with short arcs across fixed gaps. The advantage of a long arc configuration is that higher voltage and less current can be used than with short arc configurations for the same power output. This arc arrangement also appears to provide more uniform heating of the entire gas flow, increased efficiency, reduced contamination, and a suppressed column motion, thereby reducing significant electrical and aerodynamic fluctuations in the resulting plasma stream.

Plasma generators have definite measurable, but not predictable, electrical characteristics. The amount of arc voltage a particular unit will need for stable operation depends on the arc current, gas mass flow rate, arc chamber pressure, the magnetic field imposed, and the type of

gas used, besides the electrode geometry. The general arc characteristic is a sharp voltage drop from infinity to a fixed value for increasing current values and constant values of the other parameters. The general voltage-current curve is affected by the gas mass flow rate, arc chamber pressure, and the magnetic field, in that for higher values of these parameters the voltage is higher for a particular current. The type of gas also affects the operating curve in that each gas has its own ionization voltage, etc., which affect the position of the arc characteristics with respect to the voltage for a particular current.

B. Power Supplies

Consideration of the available literature indicates that the use of direct current power rather than alternating current or radio frequency power is best for plasma generator operation. Reasons for this choice other than the possible availability of a large power output direct current power supply include:

1. Less fluctuation would be expected in the resulting plasma stream with direct current operation than with the others, particularly alternating current.
2. The utilization of the differences between anode and cathode properties in electrode design.
3. The avoidance of possible "re-strike" difficulties with the use of alternating current.
4. More rapid and valid progress would be made in building a direct current unit because more information is available concerning direct current units than for the other possibilities.

Various general considerations and empirical operating evidence indicates that the optimum arc stability is obtained over a wide range of operating current by the use of a power supply with a relatively high ratio of open circuit voltage to operating voltage. This is due to a sharp intersection of the characteristic of the power supply with the characteristic of the arc. Also, a relatively small ratio of short circuit current to operating current is a desirable feature in order to prevent possible damage to the power supply. The above two power supply requirements determine a drooping voltage-current characteristic with a fairly large slope.

The various direct current power supplies available for high power steady operation include: direct current generators; welding generators; synchronous converters; rectifiers; and batteries. Of these possibilities only the welding generators and some of the direct current generators naturally have the necessary output characteristic. The others need to operate with a series resistance in order to be of use. The availability of a large power output synchronous converter power supply in part determined the plasma generator selection for this study. Therefore it and the adaptation for use are discussed in detail in the following sections.

III. PLASMA GENERATOR DESIGN CONSIDERATIONS

A. Description of the Power Supply

The available power supply consists of a nominally rated 300 KW (at 600 V and 500 a) General Electric synchronous converter and a modified set of automatic station control equipment, as shown in Figures 3 and 4. The converter is a six-phase type. The automatic station control equipment

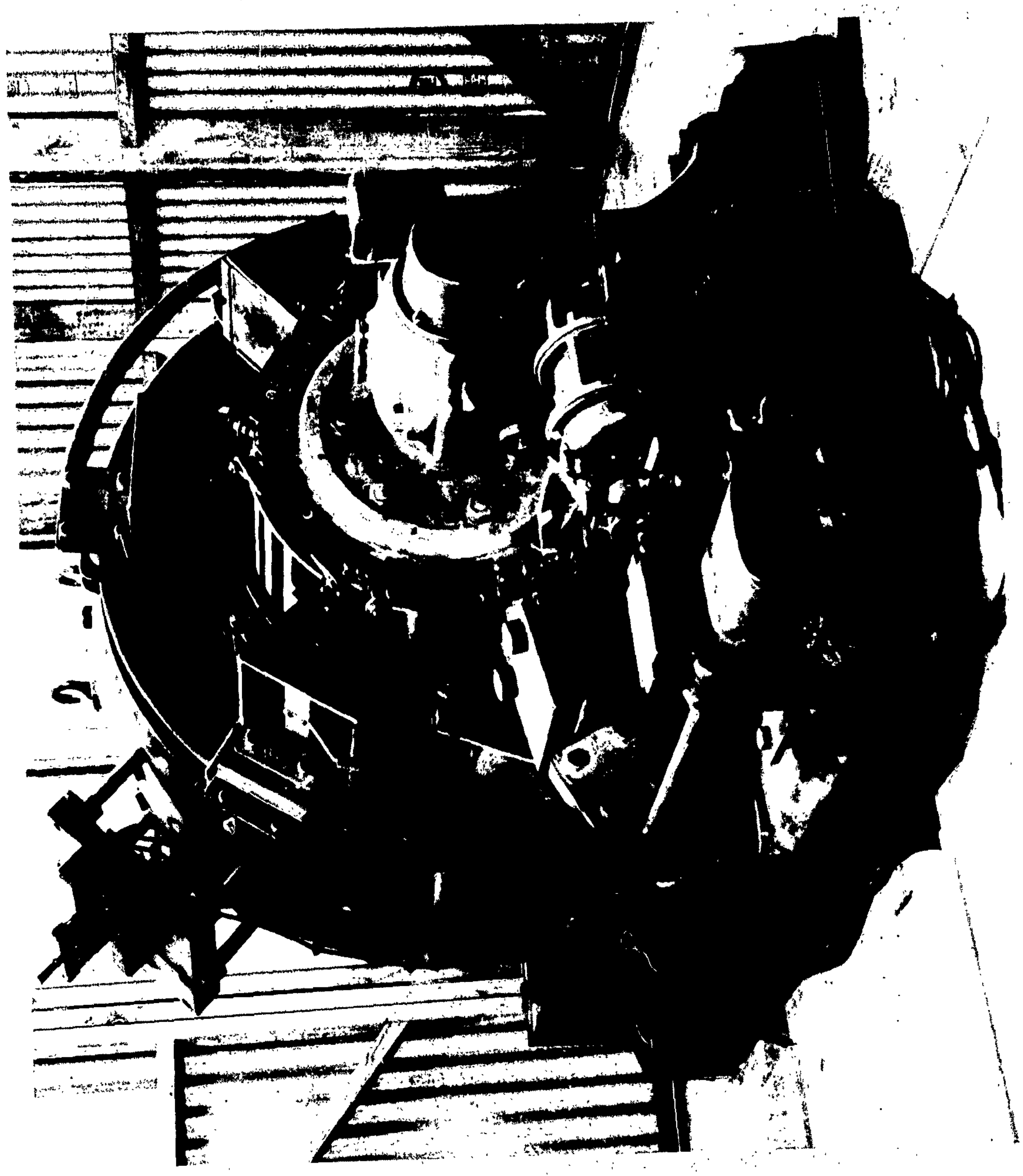


FIGURE 5. THE SYNCHRONOUS CONVERTER

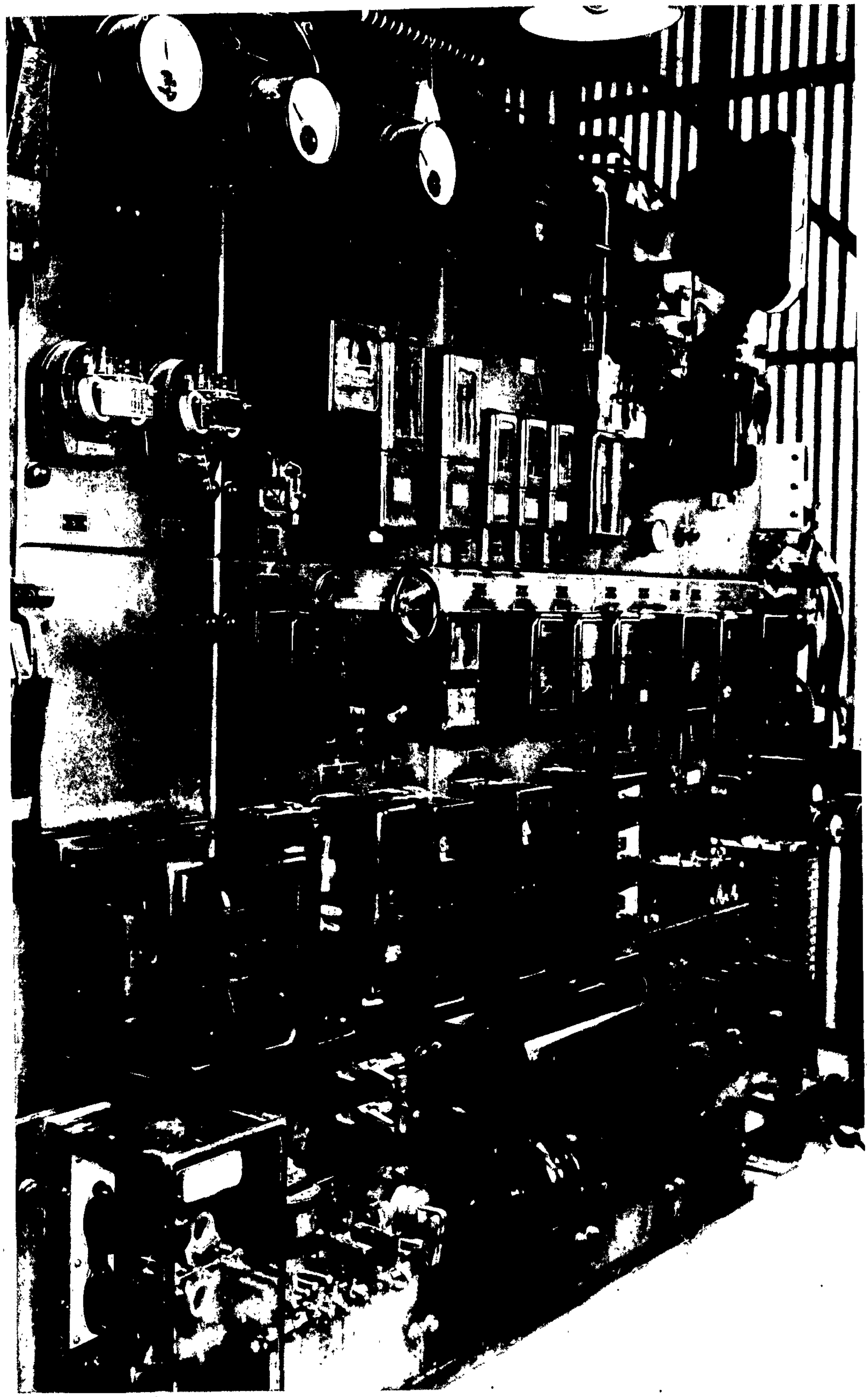


FIGURE 4. THE AUTOMATIC CONTROL EQUIPMENT HYD 7944

is designed to start, control, stop and protect the converter from internal and external hazards. This equipment has been modified to permit the power supply to run electric arcs by the permanent inclusion of an air cooled cast iron resistor bank in the converter circuit. The control equipment includes a device which can vary the direct current output voltage from about 520 V to 670 V by adjusting the phase of the alternating current input. This, with the included protection resistor, gives some degree of control over the current. The power supply also has adjustable current protectors which are now set at a maximum to limit the output to some 1500 amperes, and so while the nominal rating is for continuous operation at 500 amperes, the power supply is capable of short term operation up to 1500 amperes. This is satisfactory for the intended usage because run times in excess of ten minutes will probably not be required.

The specific voltage-current characteristics, shown in Figure 5, show the capability of the synchronous converter power supply with and without the protection resistor for the range of voltages and currents available. The curves for the system without the resistor are seen to be flat, while those including the resistor drop linearly. The range of plasma generator operation afforded by the power supply itself is quite limited and at current levels that are straining the equipment. Therefore, for safer and more flexible operation of plasma generation units a suitable, larger, variable ballast resistor is needed. This could either supplement or replace the existing resistor.

B. Selection of the Plasma Generator

A careful review of the literature was made in preparation for the design of the plasma generator for use with the synchronous converter power supply. Several descriptions of plasma generators which operated

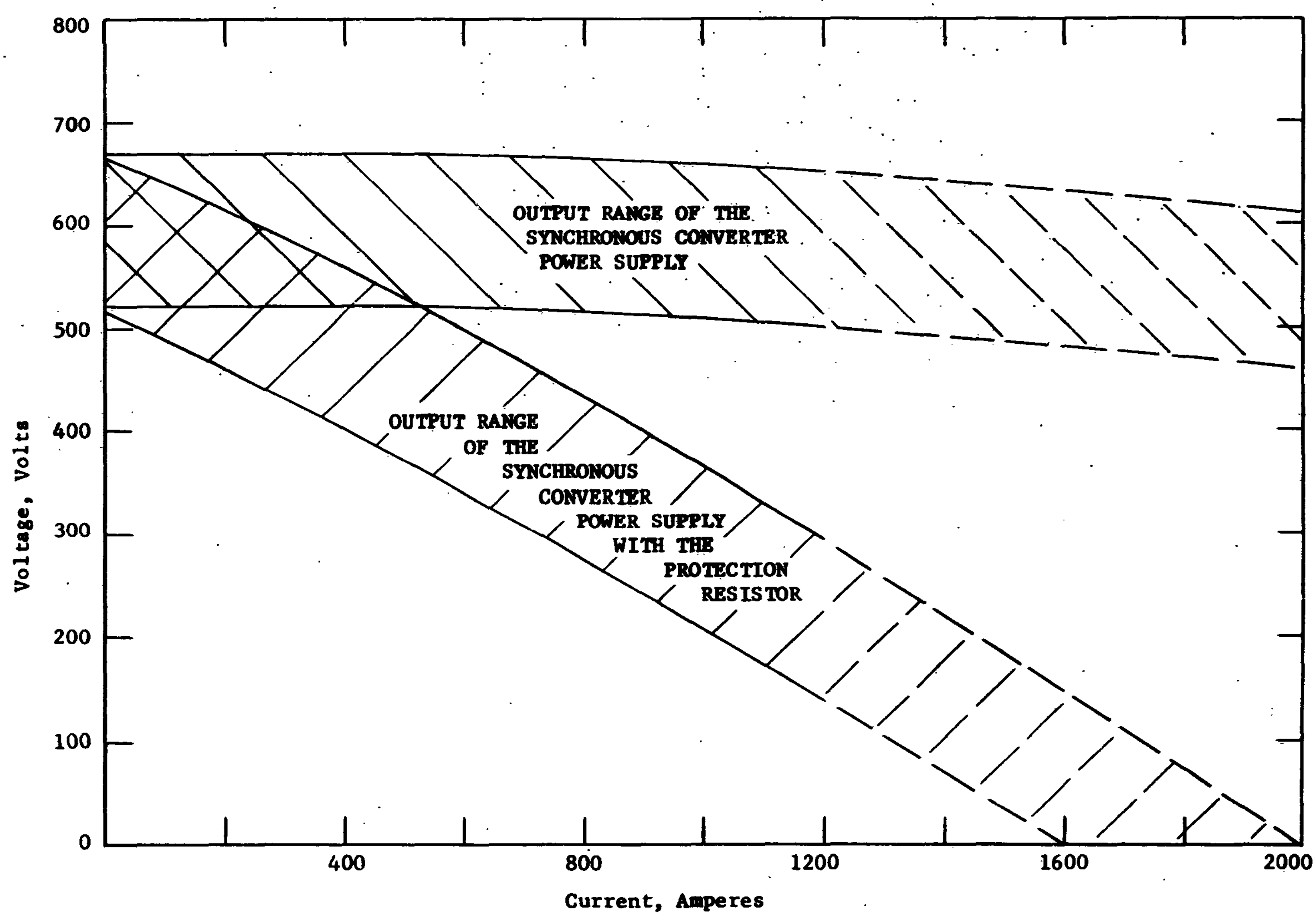


FIGURE 5. THE OUTPUT CHARACTERISTICS OF THE SYNCHRONOUS CONVERTER POWER SUPPLY

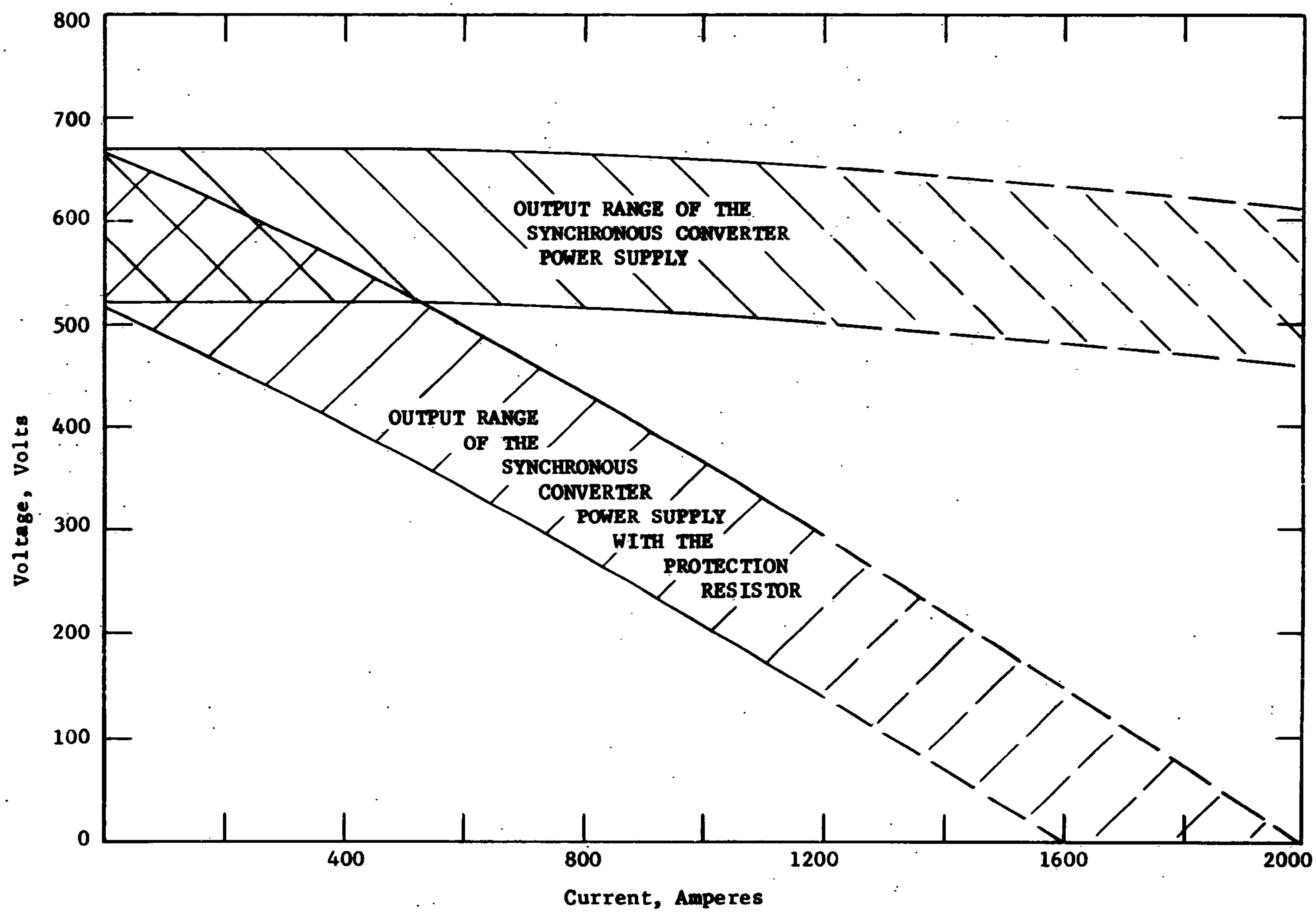


FIGURE 5. THE OUTPUT CHARACTERISTICS OF THE SYNCHRONOUS CONVERTER POWER SUPPLY

at mid-range voltages and filfilled many of the other desired features discussed in the introduction were found.[7,9,20] The two most interesting units were of the constricted configuration classification. They were similar enough so that a single piece of equipment in which either could be incorporated was considered. This could be accomplished by simply interchanging the rear electrode and the polarity. Such an arrangement would allow two types to be tested with the anticipation that at least one would prove operable without having to build two separate pieces of equipment. The two plasma generator models selected for study will be denoted as the tip-tube plasma generator (Figures 6 and 7) and the tube-tube plasma generator (Figures 8 and 9). Actually, the tube-tube unit was initially considered, and upon further investigation the tip-tube unit evolved. The tube-tube unit was modeled on a unit developed by the Speedway Research Laboratory[9] and the tip-tube unit was based on common practice.[6,8,19,20]

With the choice of the actual models to be built and tested more rigid criteria to which the actual models could be designed were established. These included:

1. The capability for operation at power levels of at least 500 KW where the voltage and current can be as much as 700 V and 1500 a, respectively.
2. The capability to handle cooling loads of at least 250 KW.
3. Non-magnetic construction material.
4. The capability to withstand at least 250 psig internal gas pressure.
5. The capability to withstand at least 150 psig cooling water pressure.

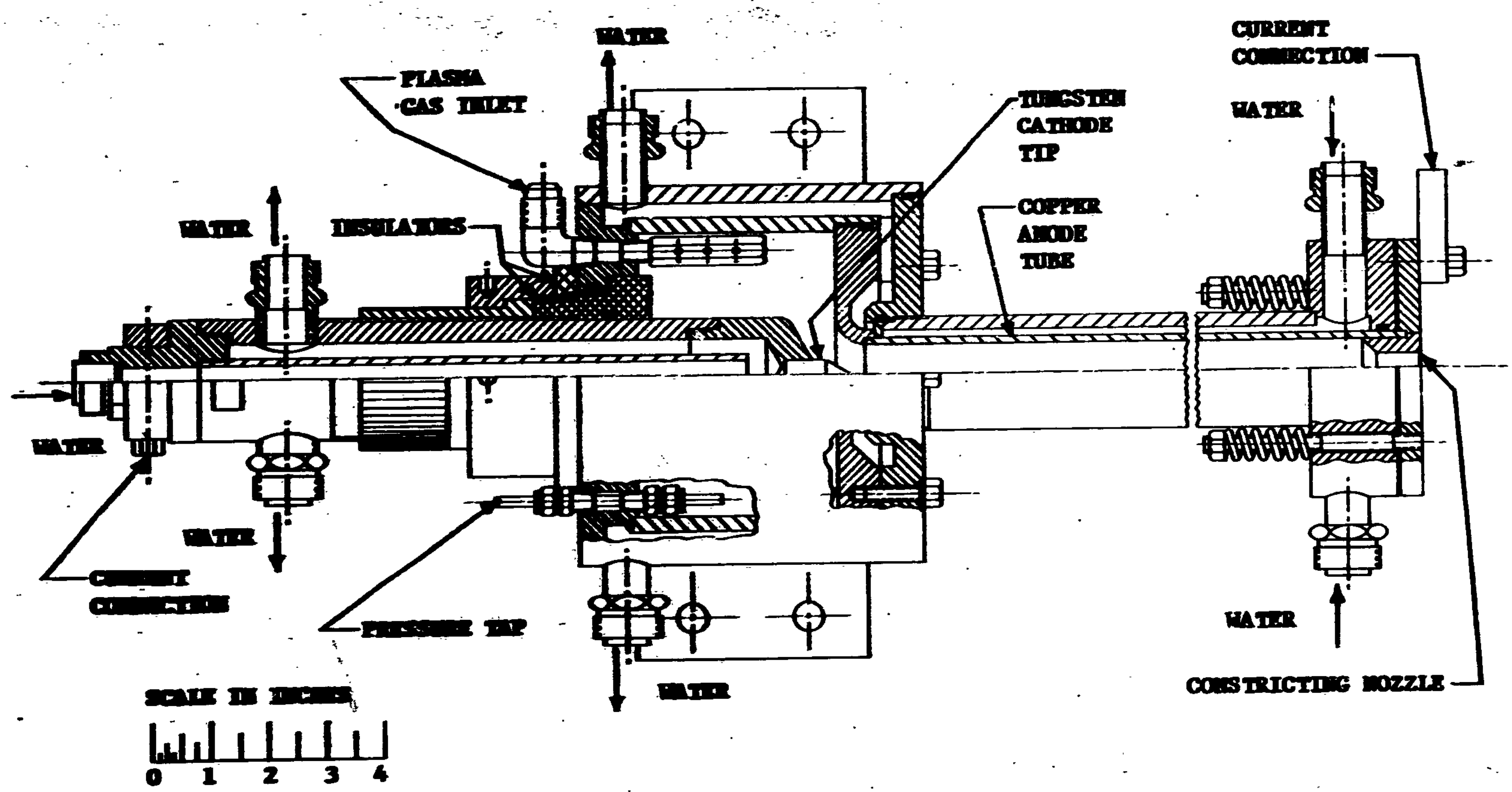


FIGURE 6. THE TIP-TUBE PLASMA GENERATOR

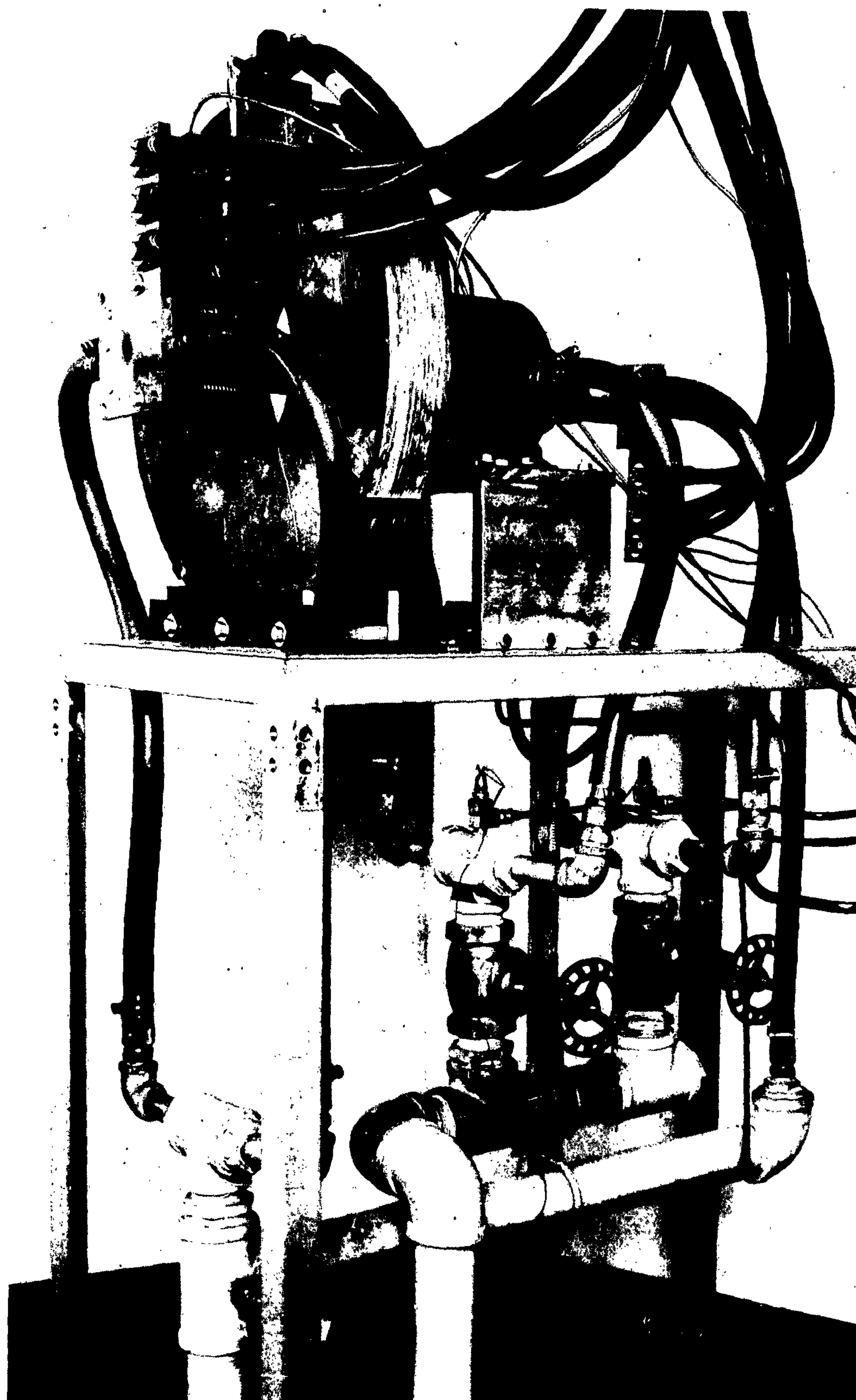


FIGURE 7. THE TIP-TUBE PLASMA GENERATOR ON THE TEST STAND

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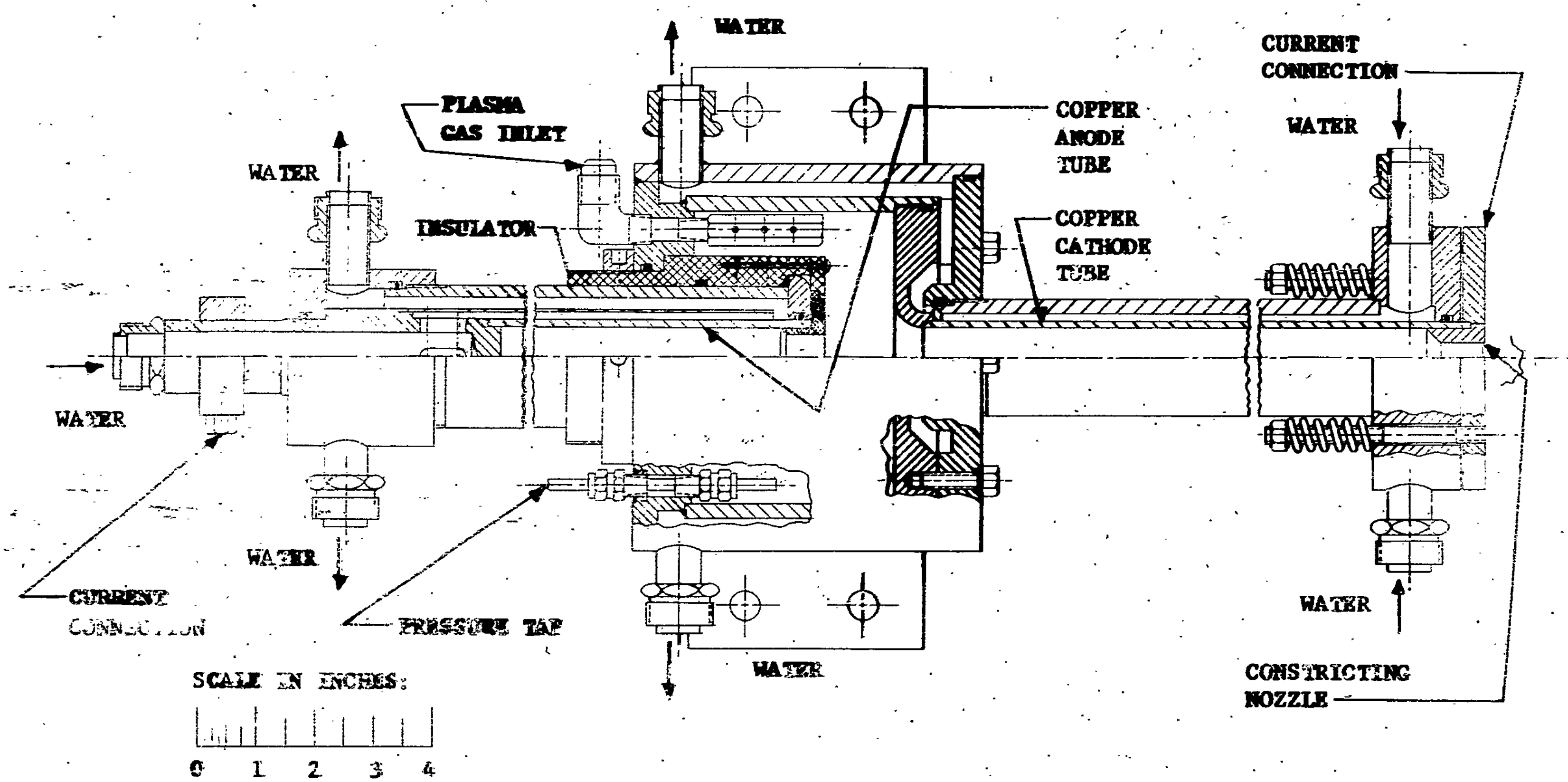

FIGURE 8. THE TUBE-TUBE PLASMA GENERATOR

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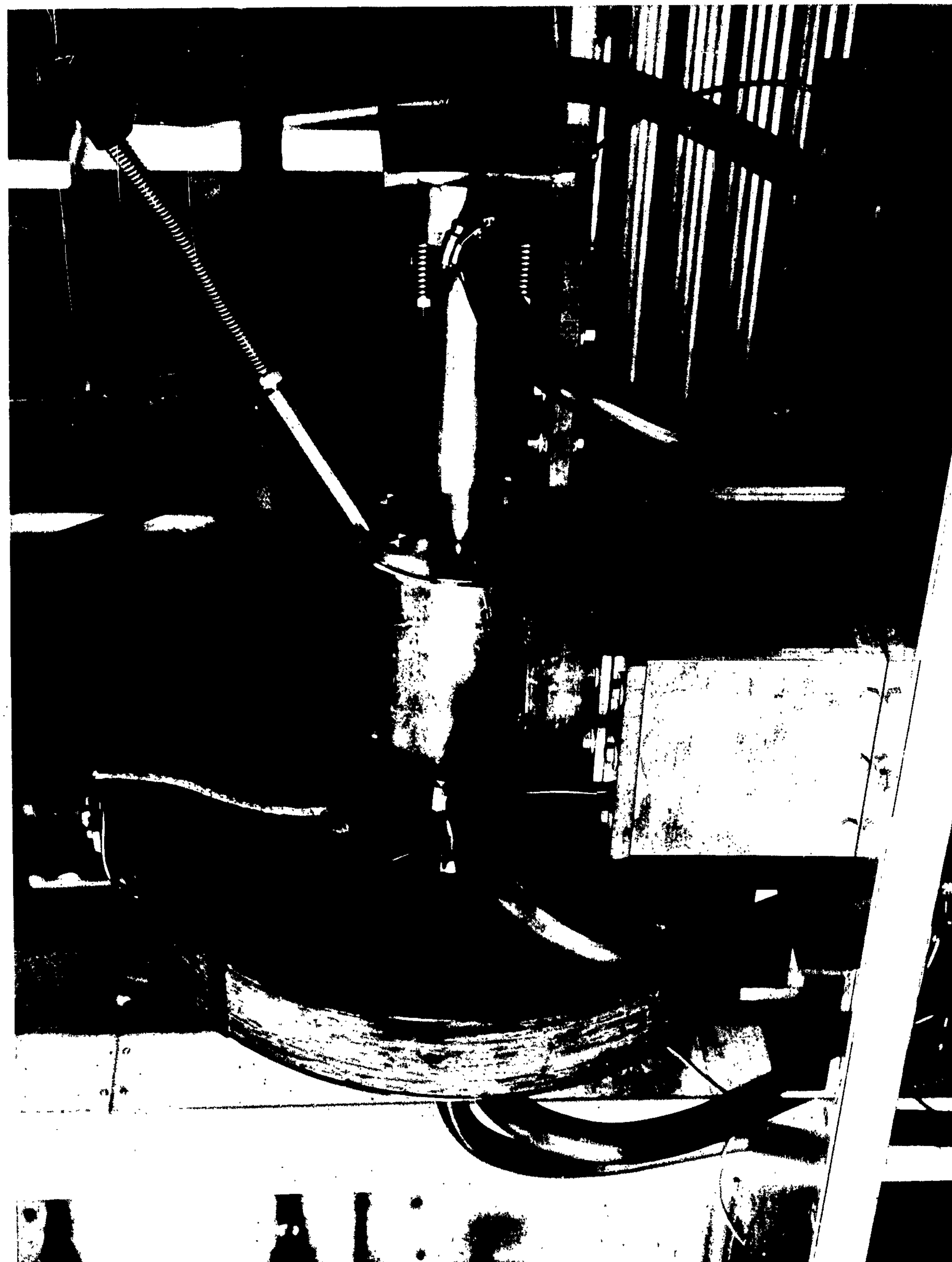


FIG. T-TUBE PLASMA GENE MOUNTED IN NTAL POSITION

6. High temperature operation, thus necessitating high temperature capacity parts, assembly and seals.
7. Allowance for the thermal expansion of the electrodes.
8. Flexibility in the mode of injection of the plasma gas in both the amount and type of flow (i.e., tangential, radial, axial, and combinations).

The physical dimensions of the device were dictated by the desired one inch nominal plasma stream diameter, the need for high cooling water velocities over the high temperature and heat flux regions, general appearance and construction details.

The plasma generator models were designed and constructed in accordance with the above criteria. These models and the final support system necessary for their operation are described in the following sections.

IV. DESCRIPTION OF THE SYSTEM

The plasma generation system constructed is described in this section. Included are details of both plasma generators and a discussion of some of the less obvious features of the system.

A. The Overall System

The arrangement of the plasma generation system developed is illustrated in Figure 10. The overall equipment layout was principally determined by the location of the synchronous converter power supply and the availability and type of space near it. The requirements for convenient accessibility in order to control, adjust and use the support equipment such as the ballast resistor, magnet power supply and the plasma gas supply also influenced the arrangement shown. The high flow rate and

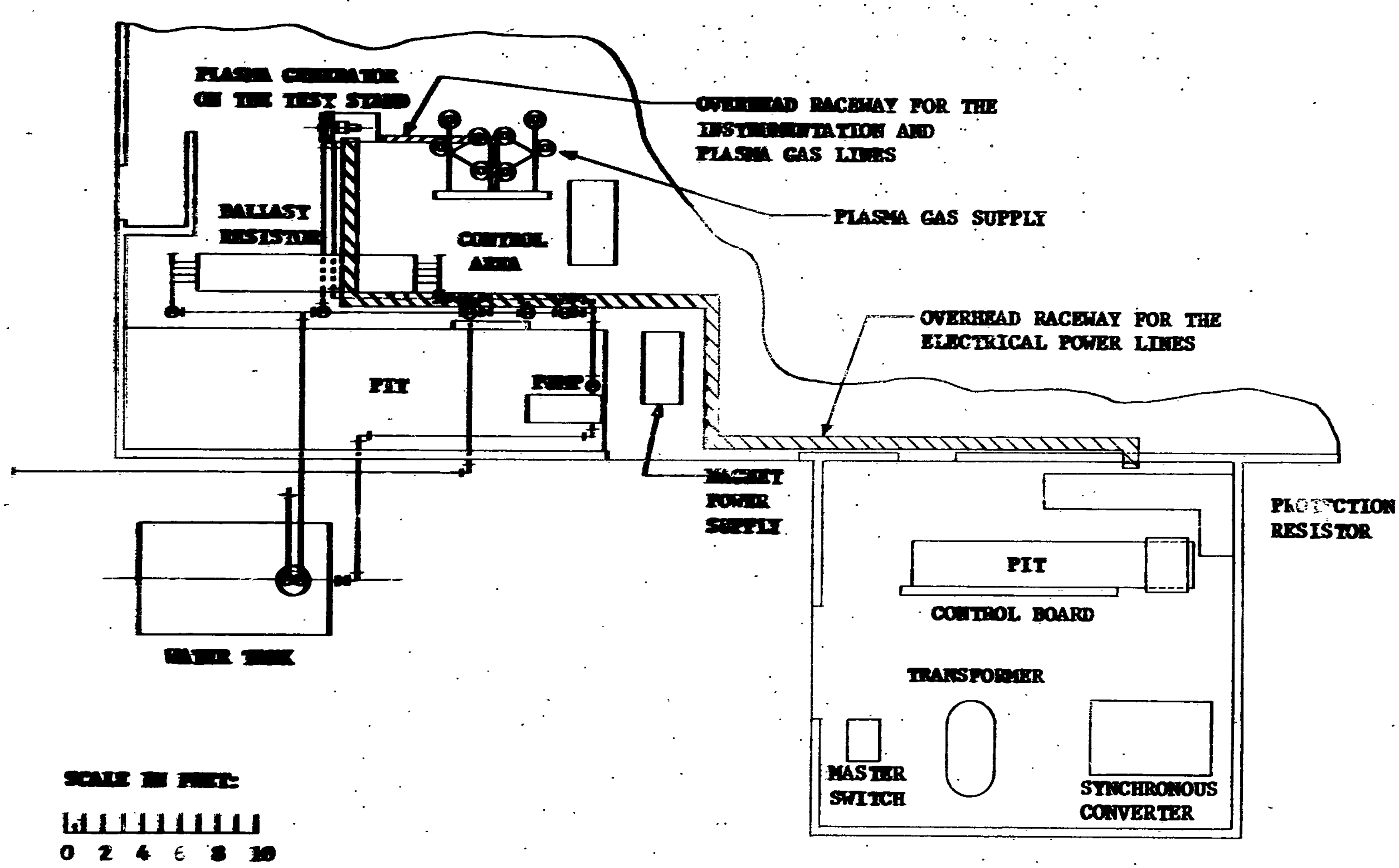


FIGURE 10. ARRANGEMENT OF THE PLASMA GENERATION SYSTEM

head requirements of the cooling water subsystem necessitated the outside tank, pit-mounted pump, and the piping layout shown. The placement of the control area which encompasses the controls for the electric power, cooling water, plasma gas supply, and the instrumentation is such that the entire operation of the system can be carefully monitored in one place by two operators. This is for safety, and of course convenience. The test stand was positioned so that the plasma generator mounted on it and the resulting plasma stream could be easily and safely observed. Also, the arrangement allows room to set up experiments to study the resulting plasma stream.

B. The Plasma Generators

The tube-tube plasma generator considered (Figure 8) consists of a water-cooled, closed-end tubular anode, a water-cooled tubular cathode ending with a simple converging nozzle, and an enlarged-diameter chamber connecting the in-line anode and cathode. An auxiliary spring loaded arc-igniting electrode was also installed for starting the device. A previous investigation[9] indicated that after ignition the arc in such a unit extends from an area inside the anode near the closed end to an area inside the cathode near the outlet nozzle. Results were presented for arc voltages from 300 to 2200 volts. Since the power supply available for the present investigation could operate in the lower part of this range, it was decided to investigate the use of this plasma generator arrangement. A magnet had also been used previously to reduce electrode erosion in the anode by rotating the arc, so this was included in the present study. The plasma gas injection was so arranged that it could be made tangential, axial, radial, or any combination of the three by means of various jets which could be positioned on a manifold built into the rear wall of the enlarged-diameter chamber.

The actual design (i.e., wall thicknesses, thread lengths, water passage dimensions, etc.) of the tube-tube plasma generator was based on the criteria discussed previously. Non-magnetic stainless steel was used for the body and outer shells where it was desirable to make welded joints. The electrodes were made of copper because of its high thermal and electrical conductivities, and brass was used where more durability than copper was required. In regions where high temperatures were anticipated, the joints were sealed with silicone rubber "O" rings capable of withstanding approximately 500° F. Possible thermal expansion of the electrodes was provided for by a spring loaded assembly for the front electrode and an "O" ring sealed slip joint for the rear electrode. A phenolic laminate was used for the insulation between the electrodes.

The tip-tube plasma generator fabricated (Figure 6) incorporated a water-cooled tungsten tip in place of the closed-end tubular electrode of the tube-tube device. It differed in operation from the tube-tube unit in that the tungsten tip in the rear is the cathode and the front tube is the anode. Provisions were made in the construction of the cathode so that it could be easily set at points along the axis, thus giving flexibility in the gap length, a feature not too easily obtained with the tube-tube unit.

This second type of plasma generator is similar to many units which have operated satisfactorily. It has the advantage in that the tungsten tip positions the arc attachment location on the cathode, whereas in the tube-tube unit the arc attachment location is allowed to choose its own place; this can lead to problems even though the worst heating is at the anode. The tip-tube plasma generator does have the limitation, however, that air cannot be used, as the hot tungsten tip would oxidize away very quickly. This would seriously limit the life of the unit, as well as change its operating characteristics.

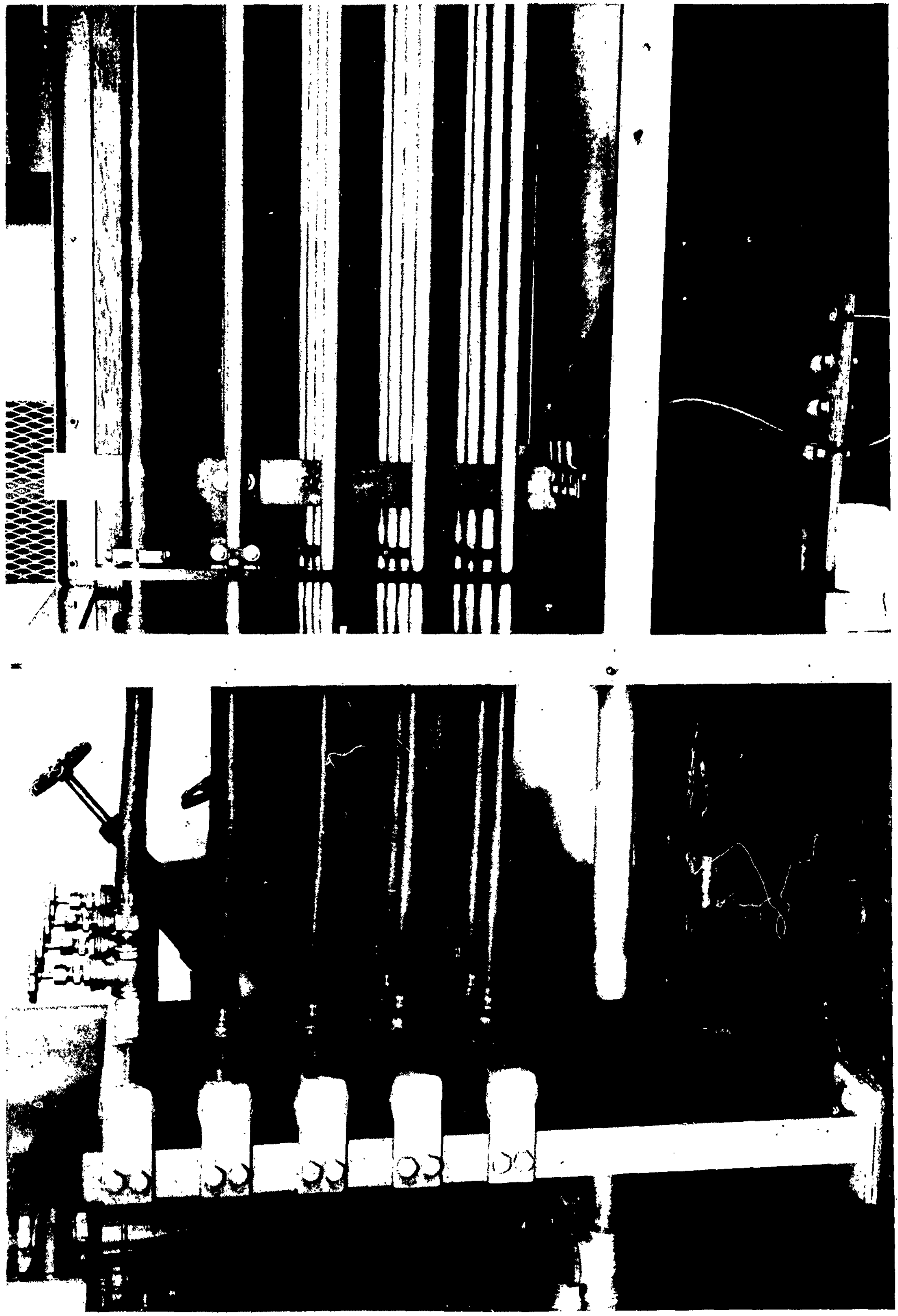
C. The Support System

* The Electrical Power Subsystem

The electrical power subsystem consists of the synchronous converter power supply, the ballast resistor, and the necessary leads and connections completing the circuit with and without the plasma generator. The power supply has been described in a previous section, and so only the ballast resistor, leads, connections and instrumentation will be treated here.

The ballast resistor, shown in part in Figure 11, was designed to provide as much flexibility as possible over the range of capability of the power supply and to be able to absorb the heating loads imposed on it up to the idealized maximum of one megawatt from the power supply. In considering the actual range of resistance needed, the idealized characteristics for the power supply, shown in Figure 12, were used. The ballast resistor which seemed to best satisfy all the design criteria was found to be a bank of stainless steel tubes arranged as shown in Figure 11. Cooling is achieved by pumping water through the tubes connected in parallel. This permits high mass flow rates which provide satisfactory cooling without a high pressure pumping system. Provisions were made to circulate the cooling water only through those tubes being used for a particular resistance setting. This was done to assure adequate cooling with only a moderate sized pumping unit. Copper jumper bars made it possible to connect the tubes in any combination necessary with the greatest resistance resulting when all the tubes were connected in series.

An optimizing study was performed in order to find the "best" tubing size for the resistor, whose length of 10 to 15 feet was fixed by space considerations. This study was based on absorbing a one megawatt



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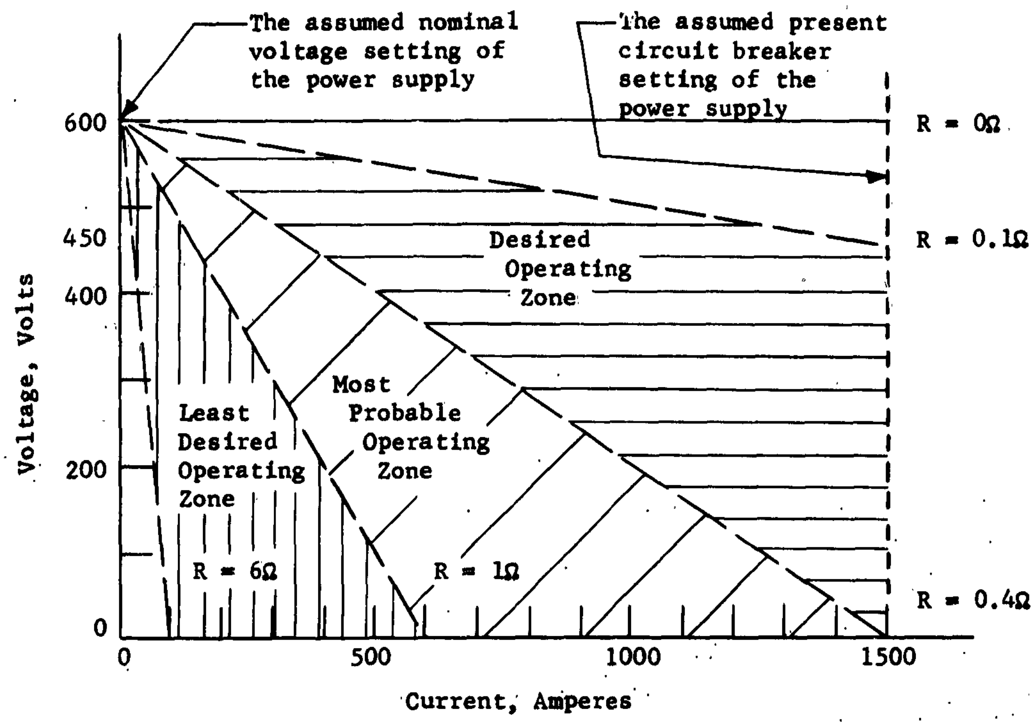

FIGURE 12. THE IDEALIZED POWER SUPPLY CHARACTERISTICS WITH DIFFERENT SERIES RESISTANCES AND THE VARIOUS POSSIBLE OPERATING ZONES

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heating load with only a 0.40 ohm resistance (i.e., the maximum condition considering the idealized operating characteristics shown in Figure 12). When this solution was completed the number of tubes was increased such that, for economic and space reasons, the ballast resistor had a 0 - 1 ohm range and could absorb one megawatt at a 0.40 ohm setting. The one ohm maximum resistance was considered adequate since low power runs which would be possible with greater resistor values up to six ohms were not of too much interest. Other factors which had to be considered were frame strength, proper tube support, proper electrical insulation from the grounded parts, cooling water manifolds, and the surface contact area necessary for a minimum of local heating.

The size of the necessary power leads and connections was based on the maximum output values for the synchronous converter power supply (i.e., 670 volts and 1500 amperes). The main power leads were made up of six No. 1 welding cables (250 - 300 amps. maximum capacity) connected in parallel. The cables were all of the same manufacture and length to assure equal current flow in each cable, since unbalanced current loadings could result in overheating and failure. The cables were mounted in expanded metal raceways attached overhead for inspection purposes and convenience. The various connectors, jumpers, and bus bars were chosen on the basis of NEMA standards.

Instrumentation was provided for observing and recording the voltages at the resistor and the plasma generator, and the current flow. A shunt was used for measuring the current. Meters indicated the voltage drops across both the ballast resistor and the plasma generator. The voltage drop across the plasma generator was also recorded on slow (Esterline-Angus) and fast (Sanborn) response type instruments. The slow response instrument provided an average voltage drop record, while the high frequency response characteristics of the Sanborn recorder provided information as to arc stability and voltage excursions.

The Cooling Water Subsystem

The primary requirement for this part of the support system was to provide a flow of moderate pressure cooling water which could absorb the possible one megawatt power output with only a moderate temperature rise. Tests indicated that the existing water supply was capable of providing about 60 gpm at 20 psig. Calculations, however, showed that more flow at higher pressures was needed to provide the cooling desired. Therefore it was necessary to build an independent water system using a

pump and a tank which could be filled from the existing water supply. The initial plan considered a non-circulating system; however, once it was determined that an independent water system was necessary, both a return line to the tank and a dump line were planned, the idea being that for high power runs the water would be dumped; otherwise it would be returned to the tank and used again.

Evaluation of the requirements of the system showed that it would be desirable to provide a flow rate of 200 gpm at which the pressure drop could be 100 psig. This resulted in the selection of a 2000 gallon steel tank and a DeLaval pump rated at 450 gpm with a discharge pressure of 65 psig. These were installed as shown in Figure 10.

The remainder of the cooling water subsystem (Figure 10) was designed on the basis of convenience, simplicity and reliability. The system was constructed so that the ballast resistor and/or the plasma generator could be operated. The flow rates in both the ballast resistor line and the plasma generator lines are controlled by globe valves, with measurements being taken of the flow by use of sharp-edged orifices and mercury manometers. Quick action valves were installed in the exhaust system to facilitate rapid change of the direction of exhaust flow when necessary. Gages for indicating the pressure at pertinent locations in the system were included. Thermocouples were also installed in the inlets and outlets of the ballast resistor and plasma generator.

<u>The Plasma Gas Subsystem</u>

On the basis of previous studies applicable to the tip-tube and tube-tube plasma generators[9,20] it was decided that provisions should be made for gas mass flow rates from 0.01 lb/sec to 0.10 lb/sec at chamber pressures to 250 psig. Although it was initially desired to build a plasma

generator to run on air, for the preliminary investigations it was considered advisable to use an inert gas to eliminate the adverse effect of oxygen. Because of the interest in eventual operation with air, nitrogen was the inert gas selected. It is also noted that nitrogen has a higher ionization potential than some of the other inert gases, which was a very desirable aspect in view of the higher power supply voltages available.

From the maximum gas mass flow rate and the maximum ten minute length of run it was seen that a capacity of 60 pounds, or about four high pressure cylinders, would be required. With additional capacity included, the system was set up as shown in Figure 10, with a nominal 8-cylinder capacity and a 10-cylinder maximum, with the option of using only four cylinders if desired. The gas manifold equipment and regulator were chosen on the 0.10 lb/sec gas mass flow rate value and the use of water pumped nitrogen, although the equipment will also operate with water pumped argon, air, or helium. The rated capacity of the regulator is slightly under the 0.10 lb/sec gas mass flow rate criterion, but it was chosen because it produced a constant delivery pressure over a range of decreasing supply pressure.

The gas mass flow rate was measured using a Fischer & Porter Stable-Vis Flowrater where the gas density in the flowrater is known from measurements of the input gas pressure and temperature. The gas pressure is monitored by a calibrated pressure gage and the temperature is measured with a thermocouple. The chamber pressure of the plasma generator is also monitored by a calibrated pressure gage.

The Magnet Subsystem

Review of the general literature showed that solenoidal magnetic fields were useful in prolonging electrode life and reducing plasma

contamination by inducing arc motion on the electrodes by means of the force resulting from the crossed electric and magnetic fields. It was also found that magnetic fields help to stabilize the arc, making possible operation at higher voltages.[7,8] The use of magnets was peculiar to each case in the literature, but the effects were general and in agreement. The maximum fields used were 5000 gauss, produced by solenoidal magnets.

Investigation of the literature concerning the tip-tube and tube-tube plasma generators[9,20] showed that a magnet was used on the anode of the tube-tube device. The reason given for its use was that it provided arc rotation in the closed-end anode tube and thus reduced electrode erosion and plasma contamination. Also, independently, it was thought that the magnetic field helped draw the arc down the closed-end anode tube, causing the arc to be longer and utilize more of the voltage of the power supply. There was little specific information concerning the magnet used in the previous investigation.[9]

The lack of firm requirements for the case at hand, despite the information from the general literature, determined the use of available equipment. The guiding thought was that once some tests had been run, a better insight would be had into the actual magnetic field needs. Therefore, an available solenoidal magnet which could be mounted for use with either the front or rear electrode with a nominal rating of some 500 gauss and a short term rating of 1000 gauss was used. It was powered by a direct current welding generator with current control. The voltage across the magnet is monitored by a voltmeter. The current through the magnet is indicated on a meter measuring the drop across a shunt.

V. TEST OPERATION OF THE SYSTEM

A. General Procedure

Evaluation of the plasma generation system was accomplished in essentially two stages. The first stage consisted of testing and calibration of the components of the system. This was done to check the validity of the design and to evaluate those capabilities not specifically determinable in the design stage. The second stage consisted of an initial exploration of the performance of the system. The actual procedures and results are rather extensive, so only a summary of the items considered is presented.

B. Equipment Checkout and Calibration

The Cooling Water Subsystem

This subsystem was installed and evaluated prior to much of the other testing because operation of much of the other equipment depended upon it. After checking the operation of the pressure gages and thermocouples installed at the various critical inlet and outlet positions, the validity of the predicted characteristics of the sharp-edge orifices placed in both the ballast resistor and the plasma generator supply lines for metering purposes was determined. The need of metering the flow stemmed from the ultimate objective of performing heat balances on the system, as well as to check out the design and cooling potential. The orifice characteristics were found to be about 5 to 10 per cent lower than predicted. The tests also showed that flow rates to the ballast resistor and plasma generator up to 120 gpm and 60 gpm, respectively, were measurable with the orifices installed and higher values to about twice those measurable were shown to be possible.

The Electrical Power Subsystem

The evaluation of this subsystem centered around the ballast resistor. The studies on the resistor included the resistance capacity and reproducibility, which compared very well with the design, in that 0 to 1 ohm was possible. Negligible resistance changes were observed during removal and replacement of the jumper bars for a particular setting. Calibration curves were prepared to show the water flow rate and pressure drop characteristics of the system. It was found that operation with 100 gpm could be effected for any tube arrangement with a maximum pressure drop of 20 psig. This is of interest because it has been estimated that 100 gpm would absorb any heating load on the resistor with only a moderate water temperature rise. Possible current losses through the hoses and water to the grounded manifolds were found to be only a few amperes--negligible in comparison to the 500 - 1500 ampere current flow expected. The several grounding leads installed for safety reasons were also checked out.

The subsystem was then set up with the plasma generator bypassed and current passed through the circuit from the synchronous converter power supply. These tests, with current levels to 1000 amperes, were very satisfactory. Results showed that the system and its instrumentation operated without any local overheating or other irregularity. Thermocouples monitoring the resistor's cooling water and tube temperatures indicated that the cooling was very adequate in that only moderate predictable temperature rises occurred. For example, for a 300 KW power dissipation in the resistor the water temperature rise recorded was about 20° F with a 100 gpm flow rate. Tube surface temperatures were about 5° F above the bulk water temperature.

The Plasma Generators

The tests performed during this part of the investigation were designed to check the integrity of the design insofar as the cooling, plasma gas flow, pressure, and electrical connections were concerned. Cooling water tests proved very satisfactory in that there were no irregularities and high flow rates were possible. Flow rate versus pressure drop calibration curves were prepared for use during operation; these showed flow rate capabilities to 50 gpm per electrode. The plasma gas flow and pressure aspects also proved very satisfactory. The devices were easily capable of operation at the 250 psig design pressure and 0.10 lb/sec design flow rate. The electrical resistance between the electrodes was essentially infinity. However, with all the service connections made, the value was about 10,000 ohm. Investigation of this apparent irregularity revealed that the various meters in the system and the cooling water lines were responsible. Fortunately, however, this magnitude of resistance was quite adequate.

The Plasma Gas Subsystem

Calibration of the gas flowrater was based on the inlet density. This enabled the gas mass flow rate to be easily but only approximately set prior to a run and then be accurately checked after the run. The gas mass flow rates possible ranged from 0.006 lb/sec to 0.136 lb/sec for gas densities of 0.075 lb/ft^3 to 0.500 lb/ft^3.

The Magnet Subsystem

This subsystem was available with the necessary calibration information desired. The range of magnetic fields possible is from 0 - 1000 gauss on the centerline with 500 gauss being the nominal maximum.

C. Plasma Generator Test Operation

Testing of the plasma generators was essentially in two parts. The first part consisted of determining that:

1. Little or no physical damage was done to the electrodes and/or other parts of the unit so that repeated operation could be conducted.
2. A plasma stream of sufficient size is produced at the exhaust of the unit.
3. Operation is stable and continuous for more than 30 seconds.
4. The arc attaches itself to the electrodes as designed.

The second part of the test operation consisted of determining physical performance characteristics of each unit. The results from this part are presented and discussed in a following section.

For these initial tests all the plasma generator parameters were set at what were estimated to be mid-range conditions, and only the gas mass flow rate was varied. The pertinent geometry parameters were such that the electrode spacing was fixed in each unit and a 0.50 inch diameter exit nozzle was used. The plasma gas (nitrogen) was injected tangentially into the arc chamber to induce arc rotation and thus extend electrode life. The magnetic field strength when the magnet was used was set at about 500 gauss for all of the runs.

The starting of the plasma generators was always accomplished quickly and simply by the use of an exploding wire arrangement. Cooling water flow rates were set at the maximum in order to prevent overheating of the electrodes and the other parts exposed to the arc. The inlet and outlet temperatures of the cooling water were monitored, but for the flow

rates used there was no appreciable temperature rise (i.e., 1° - 2° F). It was intended that the temperature rise be used to obtain an energy balance, but calculations showed that the water flow rates for a measurable change (i.e., 5° - 15° F) might cause the unit to suffer damage before this investigation was completed.

The Tube-Tube Plasma Generator

Testing of the plasma generators started with the tube-tube unit mounted in a horizontal position using the magnet as shown in Figure 9. The initial operation of the unit without adequate anode insulation proved unsatisfactory, as did a number of subsequent operations following modifications of the insulation around the anode. A plasma was produced, but the arc would not go back into the anode tube where there was adequate cooling; it appeared that the arc favored the lower part of the horizontal tube where the molten remains of the starting wire plus any melted portion of the electrode collected. Therefore, it was decided to mount the device in a vertical position and insert an insulating sleeve in the entrance of the anode tube, as shown in Figure 8. Operation was first attempted with a horizontal arrangement because it allows more accessibility by experiments using the resulting plasma stream.

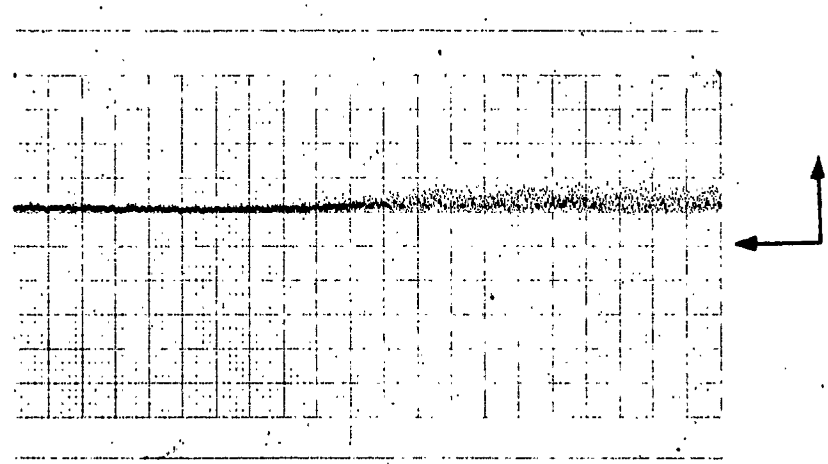
Runs with the vertical arrangement were more satisfactory, and it was shown that operation was satisfactory. The arc was stable and the attachment points were as designed. The anode attachment point of the arc was in the closed-end tube just below the insulating sleeve, and it rotated around because of the magnetic field. The cathode attachment point of the arc was in the front electrode tube near the entry from the enlarged diameter chamber, and it rotated around in the same direction as the anode point because of the tangential plasma gas injection. However, once

satisfactory operation was achieved, it was found that only single runs could be made. This was because failure of the silicone "O" ring seal at the end of the anode, due to overheating, resulted in a water leak when the arc was extinguished.

Some of the operating points from the satisfactory runs are shown in Figure 14. The testing of the tube-tube unit ended at this point due to time considerations and the desire to investigate the tip-tube unit.

The Tip-Tube Plasma Generator

The tip-tube unit was mounted in a horizontal position, as shown in Figure 7, initially without the magnet around the anode. It was found to operate very well, satisfying all the criteria for successful operation. The arc ran from the tungsten cathode point down to about the middle of the anode tube, where it rotated around because of the tangential plasma gas flow. The one problem was that while the time average power input was constant, the arc



CONDITIONS: 1 cm/sec CHART SPEED
250 V/cm VERTICAL SCALE
0.015 lb/sec PLASMA GAS FLOW RATE
485 amp. ARC CURRENT

FIG. 13. RECORDER TRACE OF THE VOLTAGE VARIATION DURING THE INTRODUCTION OF A 500 GAUSS FIELD ON THE TIP-TUBE PLASMA GENERATOR AS PER FIG. 7

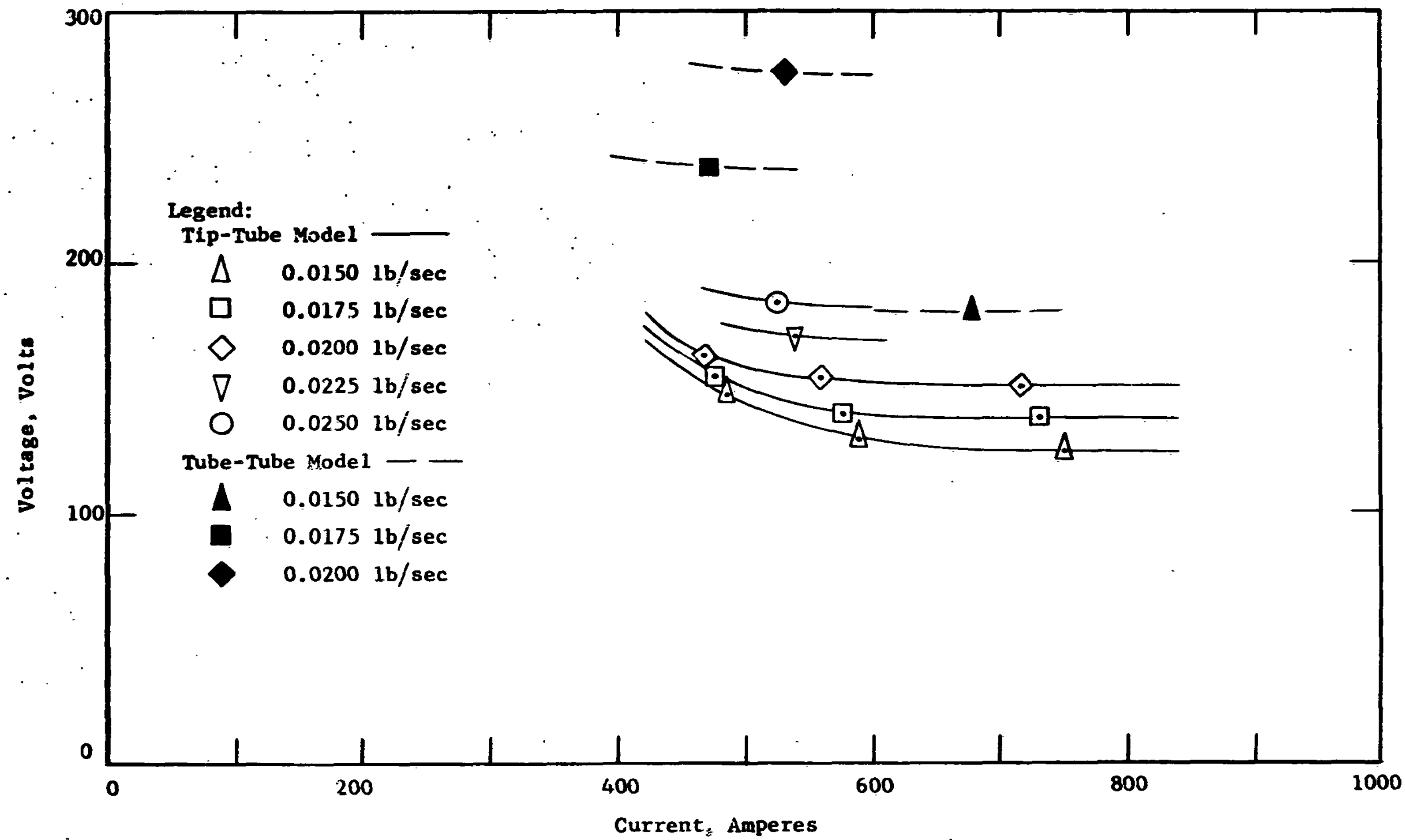


FIGURE 14. THE PLASMA GENERATORS' VOLTAGE VERSUS CURRENT CHARACTERISTICS

was not too stable. The instability caused the arc to blow out when attempts were made to increase the gas mass flow rate, thus severely limiting the flexibility. The magnet was then positioned around the mid-point of the anode tube, as shown in Figure 7, to see what its effect would be. A Sanborn recorder trace of the arc voltage, shown in Figure 13, shows the effect on the stability of the arc as the magnet is turned on. It was found, in general, that the arc was far more stable, even for the comparatively low magnitude field provided. With the tip-tube unit operated as shown in Figure 7 the performance characteristics shown in Figure 14 were obtained. Operation is such that the unit can run continually and several data points can be taken per run. The main reasons for ending a run were extinguishment of the arc by too high a gas mass flow rate or the discomfort due to the continued high noise level.

VI. PLASMA GENERATOR PERFORMANCE

A. The Tube-Tube Plasma Generator

The difficulty experienced with the "O" ring seal in the anode allowed only a few runs to be made with the tube-tube unit, and of these only the three shown in Figure 14 were considered satisfactory. However, these are sufficient to identify the performance to be expected of this unit. One item of interest shown in the results is the definite measurable gas mass flow rate effect. In the highest power run the tube-tube unit utilized about 146 KW at a gas mass flow rate of 0.020 lb/sec. Assuming an approximate efficiency of 60% (Based on the work in Reference 9), the enthalpy of the plasma stream is estimated to be 4150 BTU/lb, and the temperature on the basis of References 9 and 23, 8500° R. Similar values apply to the other runs.

The anode of the unit should be rebuilt using a hard solder joint, or possibly a metal "O" ring in place of the present silicone "O" ring, so that repeated operation is possible. Then the complete performance evaluation necessary can be conducted. This evaluation should include the voltage-current characteristics with various gas mass flow rates for different subsonic nozzle diameters, free gap lengths, and types of plasma gas injection--tangential, axial, radial, and mixed. Also, other types of gas should be used, especially air, to see the effect on the equipment. Satisfactory horizontal operation of the unit would be another item of interest to investigate. The resulting voltage-current data, along with the efficiencies found in previous work[9] and resulting from work on this experiment will provide the necessary plasma stream enthalpies and approximate temperatures for studies using the unit.

B. The Tip-Tube Plasma Generator

The results obtained from the operation of the tip-tube unit are shown in Figure 14. They are typical of the performance to be expected of the unit, and provide a base for more complete evaluations. The results for this unit also indicate a measurable gas mass flow rate effect. The resulting general shape of the performance curves corresponds very well with the results of other investigators.[1,7,9,14,20,21]

Using an approximate efficiency of 75%, again gased on previous work,[20] the estimated range of plasma stream enthalpy and temperature covered by data in this investigation was 2500 - 4500 BTU/lb, and 6000° - 9000° R, respectively. Further evaluations of the existing unit covering the 200 - 1200 ampere current range and the 0.010 - 0.050 lb/sec gas mass flow rate range should provide plasma stream enthalpies and temperatures

in the approximate range of 1000 - 8000 BTU/lb and 4000 - 11,500° R, respectively. There is also a considerable amount of performance evaluation which should be done with the other parameters available, as discussed for the tube-tube unit. One exception is that air cannot be tried unles the tungsten cathode is sheathed in an inert gas.

C. The Plasma Stream

The plasma stream produced during satisfactory operation of the plasma generators was conical with a length of three to four inches. There was also an accompanying sheath of hot gas surrounding the plasma stream which flared out from the nozzle exit and was visible three to four feet away, although it was not hot at those distances. The brightness of the plasma stream and the amount of sheath appeared to depend on the enthalpy and therefore temperature level. The enthalpy, being a function of the gas mass flow rate and the power input to the gas, decreases for higher gas mass flow rates at a constant power input level. The observed effect was that for high enthalpy runs the plasma stream was very bright and a large sheath was in evidence. The brightness of the plasma stream and the sheath size dropped significantly with the enthalpy change from 4500 to 2500 BTU/lb.

The plasma stream was not formally studied in this investigation, so the degree to which it satisfied the criteria presented in the introduction is not completely assessible. Both units are capable of producing a one inch diameter plasma stream. This was not attempted, however, because of the desire to start testing at a non-extreme geometry position.

D. Techniques for Increased Performance

The desire to use as much of the output of the power supply as possible and otherwise to improve the system has led to consideration of techniques that can be used for these purposes. Reference to Figures 5 and 14 shows that a high percentage of the power has not been used in making plasma. One approach to utilizing more power is to reduce the ballast resistance. This can be done easily by bypassing the protection resistor and placing the full load on the more flexible variable ballast resistor. The result should make possible operation in the range qualitatively illustrated in Figure 15. It must be recognized, however, that with such an arrangement the stability of the arc and the current limitations of the power supply will have to be carefully watched to prevent drawing excessive currents from the power supply.

A typical technique for obtaining higher voltage, and therefore higher power operation, is the use of higher arc chamber pressures. This can be achieved by using sonic exit nozzles. There is not complete agreement on the actual effect of higher arc chamber pressures, but in general significant and measurable effects have been reported. In fact, it has been shown that the arc voltage varies as the 1/4 to 1/2 power of the chamber pressure for a particular current and constant values of other possible parameters[1]. Figure 15 shows this effect qualitatively. The plasma generators have been designed to withstand pressures to 250 psig, and can be used to investigate the influence of the arc chamber pressure to that point. Another benefit of using sonic exit nozzles is that a supersonic nozzle can be attached, providing a supersonic stream with a larger test area.

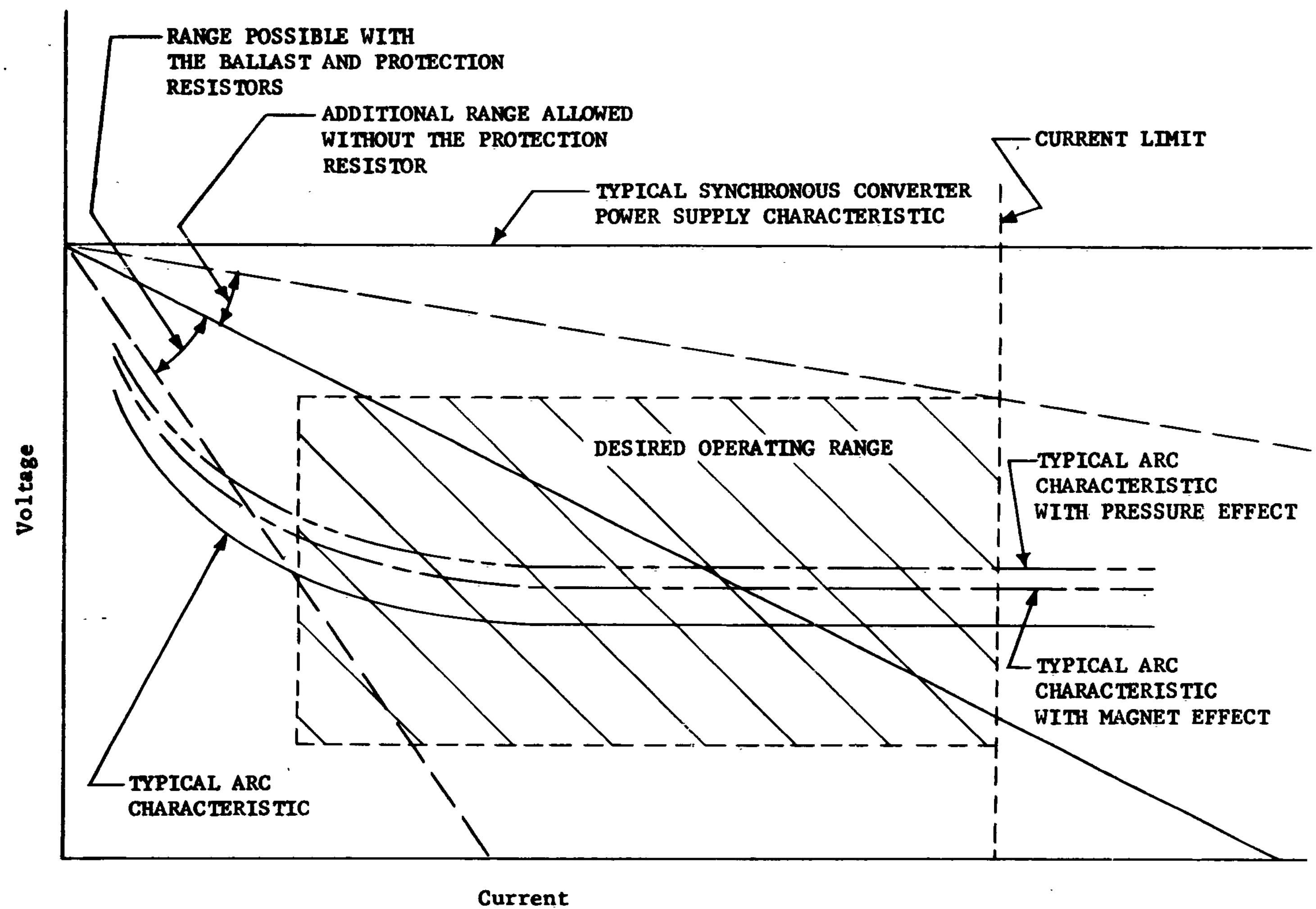


FIGURE 15. QUALITATIVE EFFECTS OF THE TECHNIQUES FOR INCREASED PERFORMANCE

Another technique for improving the power utilization is the application of magnetic fields. It has been reported that a significant increase in arc voltage results with increased magnetic fields,[7,8] as qualitatively shown in Figure 15. The magnet used in this investigation was mainly for stability, and no study was made of the effects which might be achieved by varying the field strength or position. For example, it would be of interest to have a solenoidal magnet or a set of solenoidal magnets which could be mounted around the full length of the front electrode. Field capabilities in such an arrangement to 5000 gauss would be desirable for testing this parameter, but would require water cooling for steady operation.

VII. CONCLUSIONS AND RECOMMENDATIONS

The objective of constructing an operable plasma generation system for use with the modified synchronous converter power supply was achieved. Satisfactory operation of two separate types of plasma generators was demonstrated, and representative performance data are presented. The results showed that the time average power input to the plasma stream was constant even though the arc experienced some instability. The constant time average power input is attributed primarily to the high operating integrity of the system.

The results of this investigation indicated that future effort should be directed toward increasing arc stability and the amount of power utilized by the plasma stream as well as studying and using it. The following items should be studied as possible means for achieving the desired higher power utilization, arc stability, and better operation in general:

1. The protection resistor should be bypassed and the variable ballast resistor used to explore the possibility of higher power utilization.
2. Sonic nozzles should be employed to investigate the effects of higher arc chamber pressures on the power utilization.
3. Studies should be made with various magnetic fields around the units to determine the effects on both power utilization and arc stability.
4. In the interests of thermal efficiency, the front electrode tube should be shortened such that the longest arc possible terminates just at the entrance to the nozzle instead of midway along the tube as it appears to do now.
5. The anode of the tube-tube unit should be redesigned using a hard solder joint in place of the present silicone "O" ring.
6. A suitable test section and/or tunnel should be constructed for testing the plasma stream and to damp out some of the operating noise of the unit.

Subsequent investigation of increased power input to the plasma stream should be coupled with other studies concerning the plasma stream in the interests of economy and project progress.

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